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14. ABSTRACT
On our 31st trip to the laser facility at WSMR we carried out experiments on laser ablation of black and white Delrin [also called polyoxymethylene, polyformaldehyde, (HCHO)x]. Mass ablation andthrust generation (Impulse) were accurately measured as a function of input laser energy in one shot experiments. The efficiency of conversion of laser energy to jet kinetic energy depended on thegeometry of the energy absorption/conversion zone. The most ideal geometry, an axis symmetric mini thruster, produced ~ 60 % conversion efficiency. The extensively studied 10-cm diameter Lightcraft (with inverted paraboloid, plug nozzle geometry) produced ~ 50% conversion efficiency. The upper limit to energy conversion was computed with CEA code to be 73% for the well defined mini thruster geometry. Thus, total losses amount to ~ 13% and ~ 23%. This is a significant finding and helps to validate the concept of "momentum calorimetry", in which experiments like those accomplished here may be conducted to obtain reliable heats of formation. The performance of candidate chemically enhanced laser ablation or other solid propellants may be measured on a small scale. In these most recent experiments, a near-exact match of coupling coefficients (1%) was achieved in a 14-fold scale-down of the 10-cm Lightcraft to the mini thruster.

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Comparison of Ablation Performance in Laser Lightcraft and Standardized Mini-Thruster

The 4th International Symposium on Beamed Energy Propulsion

15-18 *November 2005*

Nara, Japan

Sean D. Knecht,

C. William Larson, &

Franklin B. Mead, Jr.

Propulsion Directorate

Air Force Research

Abstract

On our 31st trip to the laser facility at WSMR we carried out experiments on laser ablation of black and white Delrin [also called polyoxymethylene, polyformaldehyde, (HCHO)x]. Mass ablation and thrust generation (Impulse) were accurately measured as a function of input laser energy in one shot experiments. The efficiency of conversion of laser energy to jet kinetic energy depended on the geometry of the energy absorption/conversion zone. The most ideal geometry, an axis symmetric mini thruster, produced ~ 60 % conversion efficiency. The extensively studied 10-cm diameter Lightcraft (with inverted paraboloid, plug nozzle geometry) produced ~ 50% conversion efficiency. The upper limit to energy conversion was computed with CEA code to be 73% for the well defined mini thruster geometry. Thus, total losses amount to ~ 13% and ~ 23%. This is a significant finding and helps to validate the concept of "momentum calorimetry", in which experiments like those accomplished here may be conducted to obtain reliable heats of formation. The performance of candidate chemically enhanced laser ablation or other solid propellants may be measured on a small scale. In these most recent experiments, a near-exact match of coupling coefficients (1%) was achieved in a 14-fold scale-down of the 10-cm Lightcraft to the mini thruster.

Outline

- Collaboration Network/Why Laser Propulsion?
- Flavor of PLVTS
- The Laser and EL measurement (Joules)
- The Pendulum and I measurement (Newton seconds)
- The Mettler Balance and m measurement (milligrams)
- Compare the EL, I, m measurements on 2 Test Articles
  – Light Craft, model 200-3/4
  – Mini Thruster Standard for momentum calorimetry/prop devel
- Elementary considerations (energy/momentum)
- Comparison of experiments to 1-D equilib code (CEA)
- Conclusions/Work in progress/Flight Tests Movie

File name

Phase II Program Collaborations
X-50LR: Experimental 50-cm Laser Ramjet

X – 50LR
Dr. Frank Mead, Jr.
Dr. C. "Bill" Larson
AFRL/PRSP

Thrust Measurement
U. Alabama, Huntsville
Dr. Andrew Pakamov

CO2 Laser: Lab & Flight Testing
HELSTF/WSMR - Mr. Steve Squires

Laser Propulsion for Navy
Michael Libeau
NSWCDD, Dahlgren, VA

Computer Launch Model
Penn State U.
Dr. Michael Micci
(Mr. Sean Knecht)

System Study
Flight Unlimited
Mr. Dave Froning

Beam Propagation
DS&S
Dr. Alan Pike

Laser Consultant
Trex Enterprises
Dr. Victor Hasson

SiC Parabolas
DARPA
Dr. Christodoulou

Attitude Control
Polaris Sensors
Mr. John Harchanko

Vehicle Fabrication
COI Ceramics
Dr. Tim Easler

Ablation of Liquid Fuels
Inst. for Laser Technology
Dr. Shigeaki Uchida

Laser Launchers
AFOSR MURI
Dr. Mitat Birkan

Ablation of Solid Fuels
Inst. of Technical Phys.
Mr. Wolfgang Schall

= Government Agencies
= Contractors
= Foreign Research

File name

Team December 2004

Pulsed Laser Vulnerability Test System

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Jim Shryne, RSI

John Harchanko, POLARIS TECHNOLOGIES

Steve Squires, Chris Beairsto, Mike Thurston,

JaySpray, WSMR/HELSTF/PLVTS

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Overall Energy Conversion in Laser Propulsion Mission

$$E_f = 1/2mv^2 = \eta\ \alpha\ \beta\ \gamma\ \delta\ E_{wall}$$

η= propulsion efficiency (jet kinetic energy to vehicle kinetic energy)
α = expansion efficiency (internal propellant energy to jet kinetic energy)
β = absorption efficiency (laser energy at vehicle to internal propellant energy)
γ = transmission efficiency (laser energy at ground to laser energy at vehicle)
δ= laser efficiency (electric energy to laser energy at ground)

******* Issue: separability of $\eta\ \alpha\ \beta\ \gamma\ \delta$ and E_{wall} *******

“ $500 worth of electricity to put 1 kg into LEO.”
At $0.10/KWH, $500 buys 18,000MJ = E_{wall} (1 KWH = 3.6 MJ);
1 kg at 10 km/s has E_f = 50 MJ, so $\eta\alpha\beta\gamma\delta$ = 0.0028 = 50/18000
But if 28% overall efficiency, then $5/kg

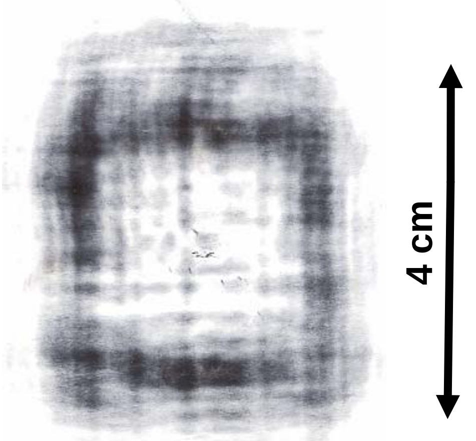
Phipps, Reilly, Campbell, *Laser & Particle Beams* 18 (2001) 661-695
Pirri, Monsler, Nebolsine, *AIAA Journal* 12 (1974) 1254-1261

Pulsed Laser Vulnerability Test System

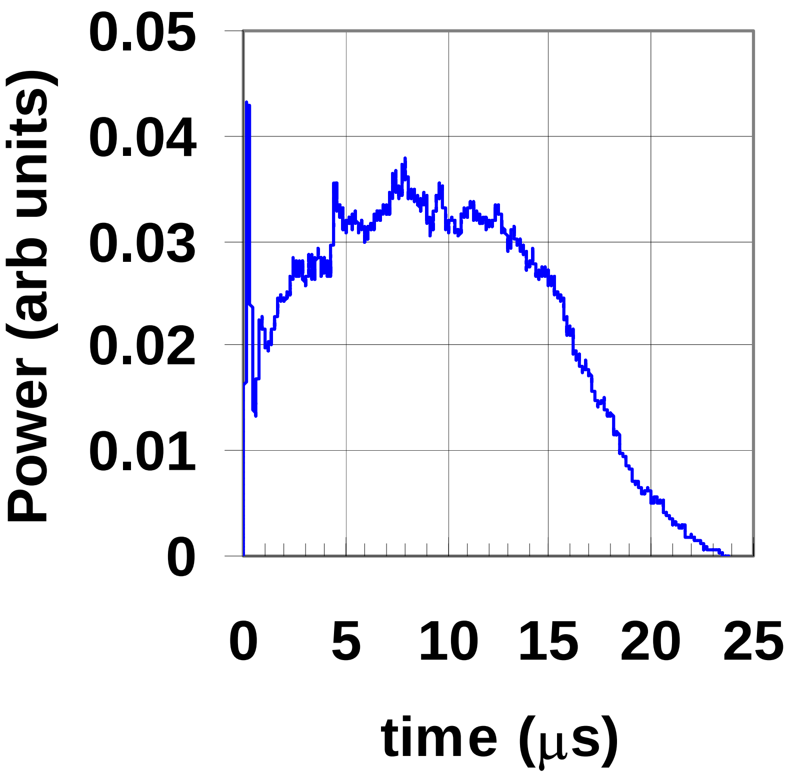
Laser Specifications

- Pulsed CO_2 Laser
- 10 KW
- ~ 5 to 30 μs pulse width
- Up to 30 Hz
- Up to 1000 J/pulse (E_L ± 10%)
- Near Field Burn Pattern

~ 10 feet



Pulse Shape



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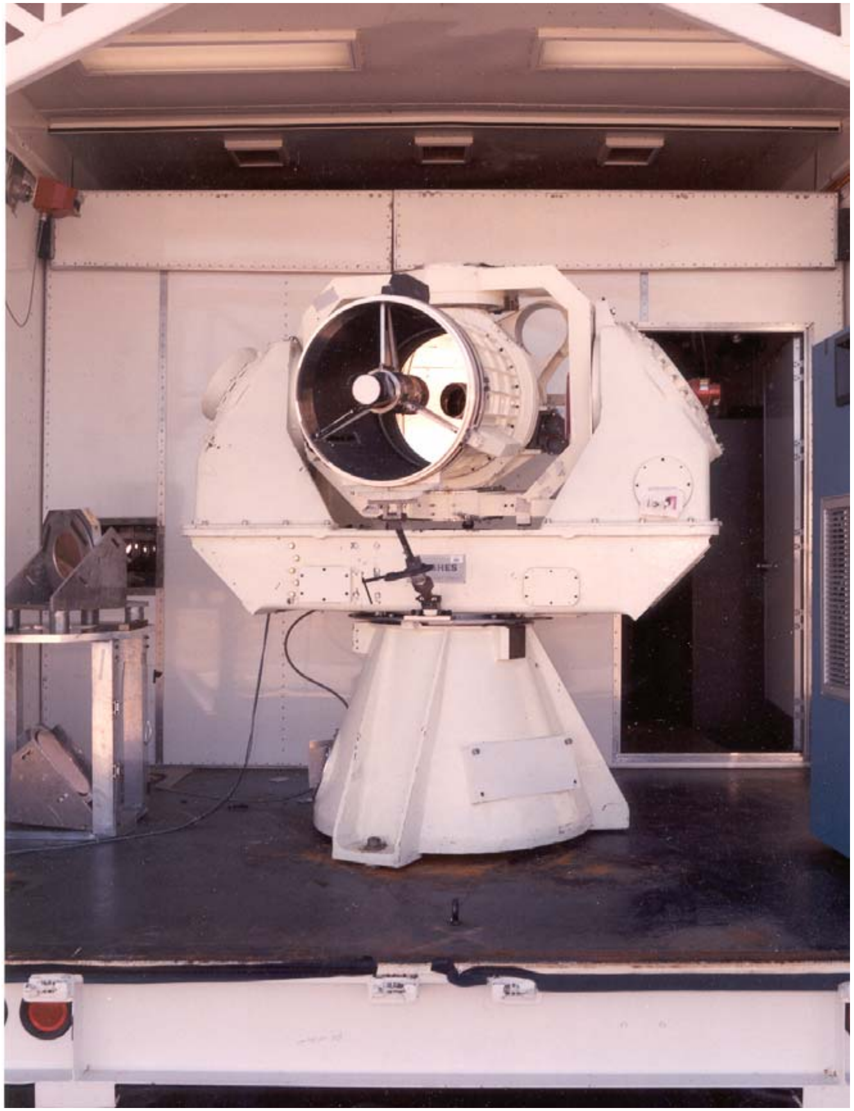
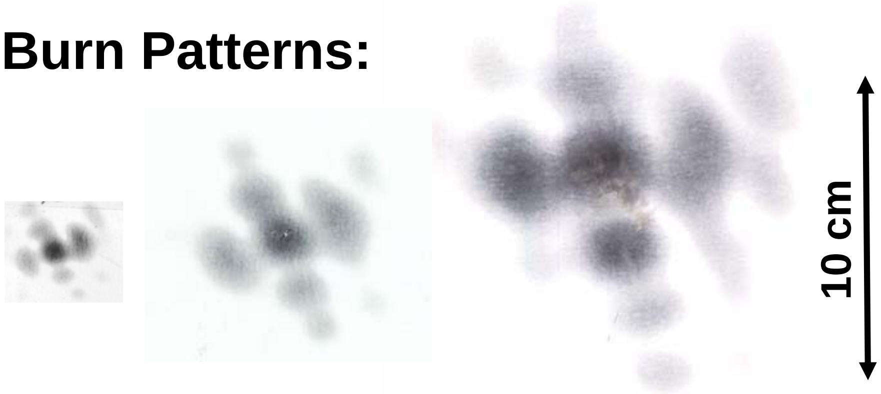
10 kW LASER IRRADIATION

FFT and Far Field Burn Patterns

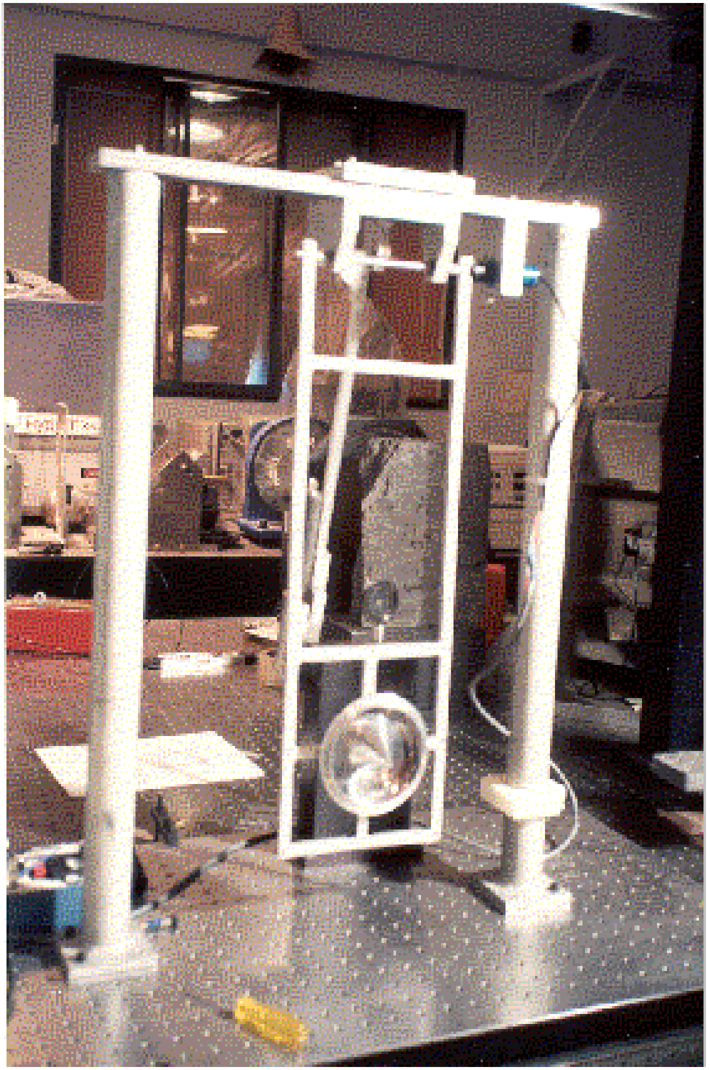


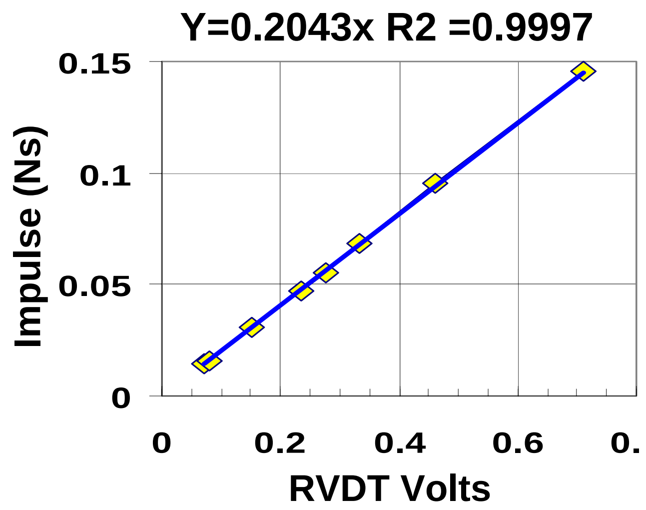
Burn Patterns:

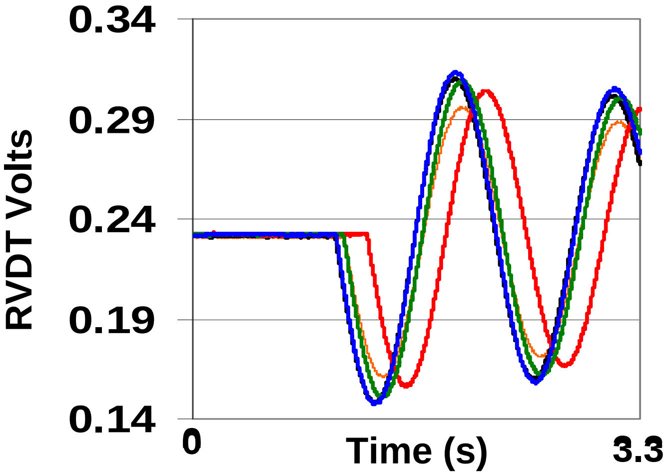


500 feet **1000 feet** **1500 feet**

Pendulum Test Stand



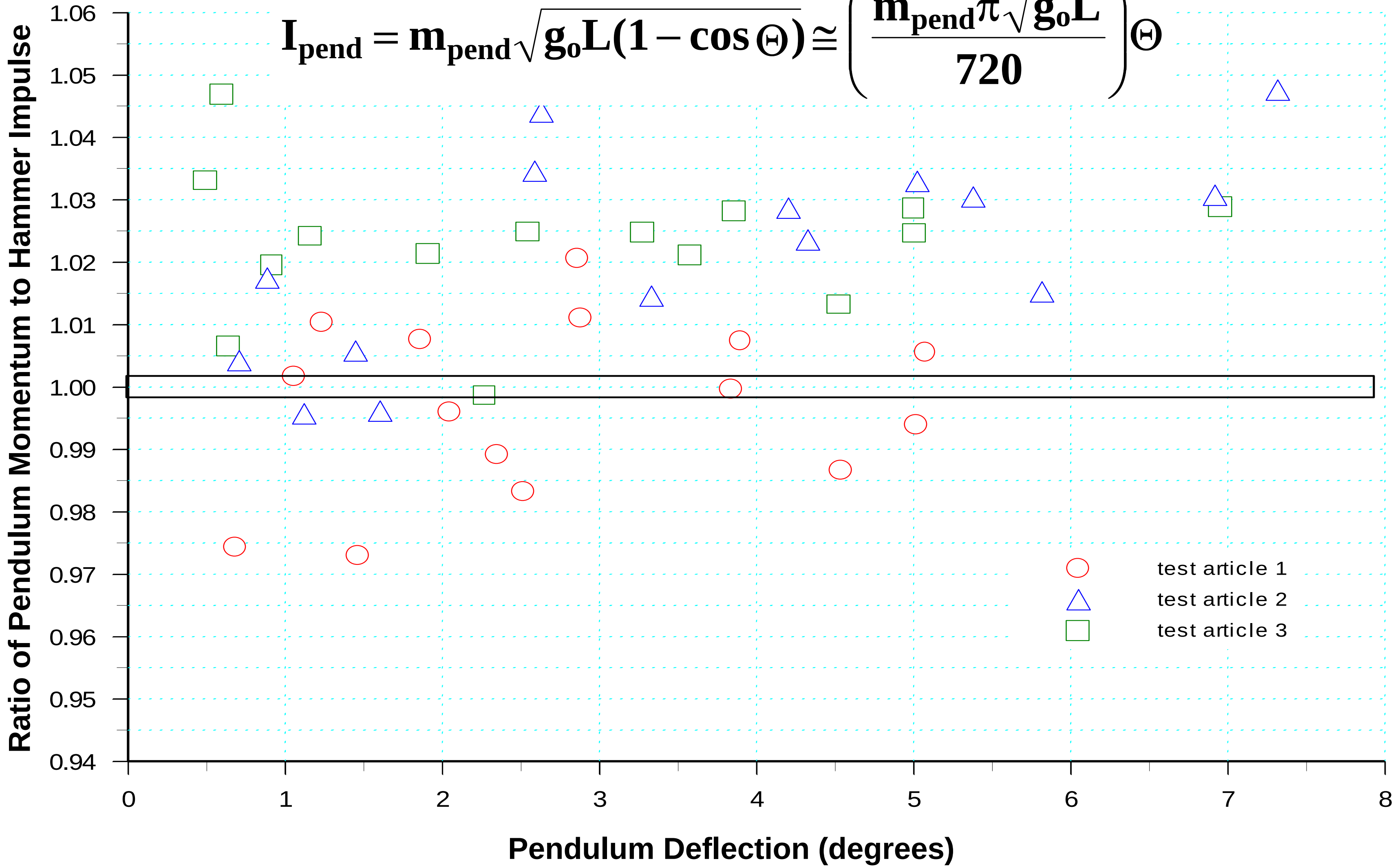




File name

Comparison of Pendulum Impulse to Hammer Impulse

$$I_{pend} = m_{pend}\sqrt{g_o L(1-\cos\Theta)} \cong \left(\frac{m_{pend}\pi\sqrt{g_o L}}{720}\right)\Theta$$



Larson, Mead AIAA 2001-0646

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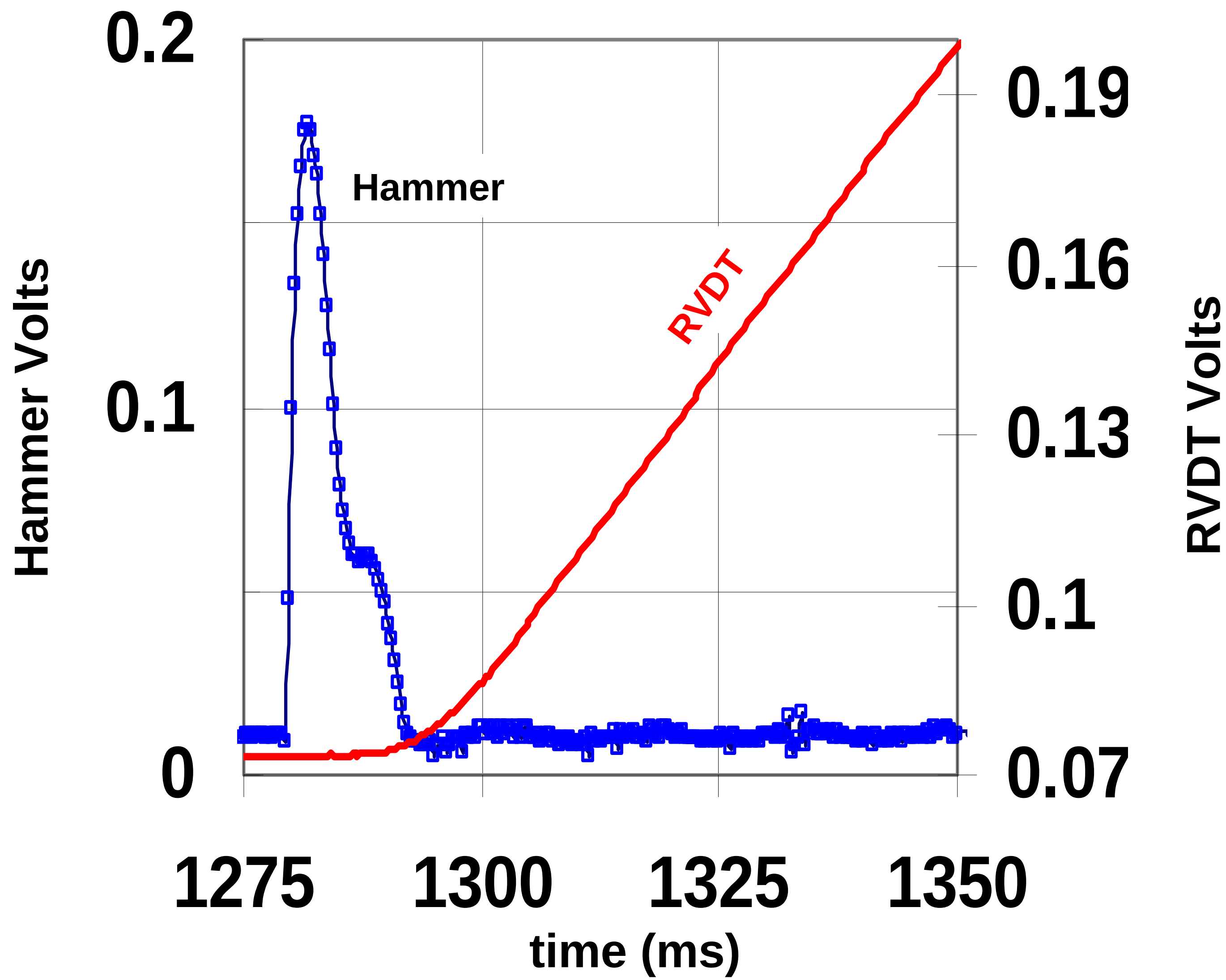
NIST Traceable Impulse Calibration



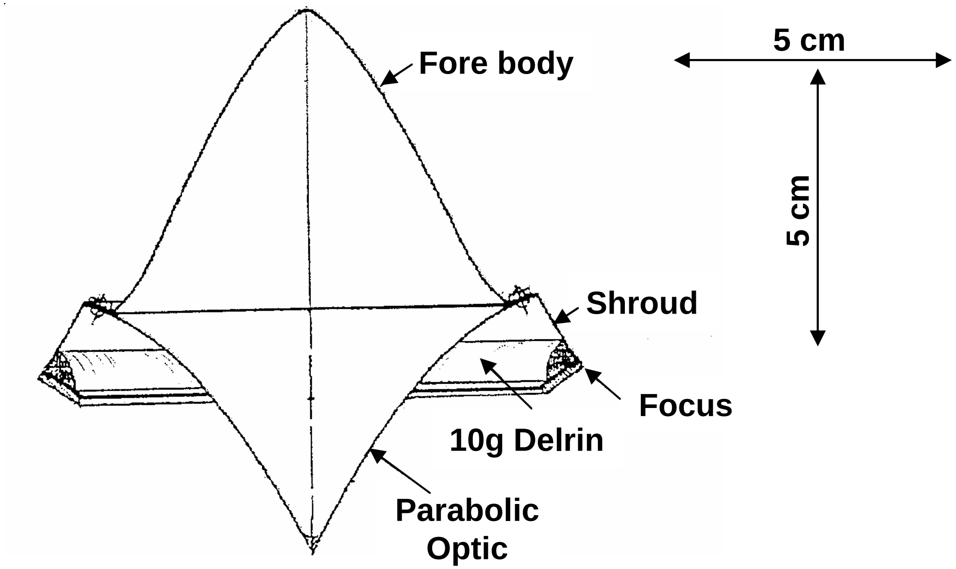
Mettler Balance or Digital Balance

Measure m to $\pm$ 0.3 mg

Model 200 Lightcraft Series: An AF-Patented Laser Vehicle Concept

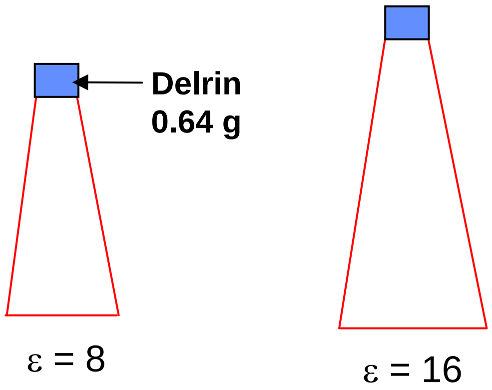
Lightcraft and Mini-Nozzle Standard

200-3/4 Lightcraft



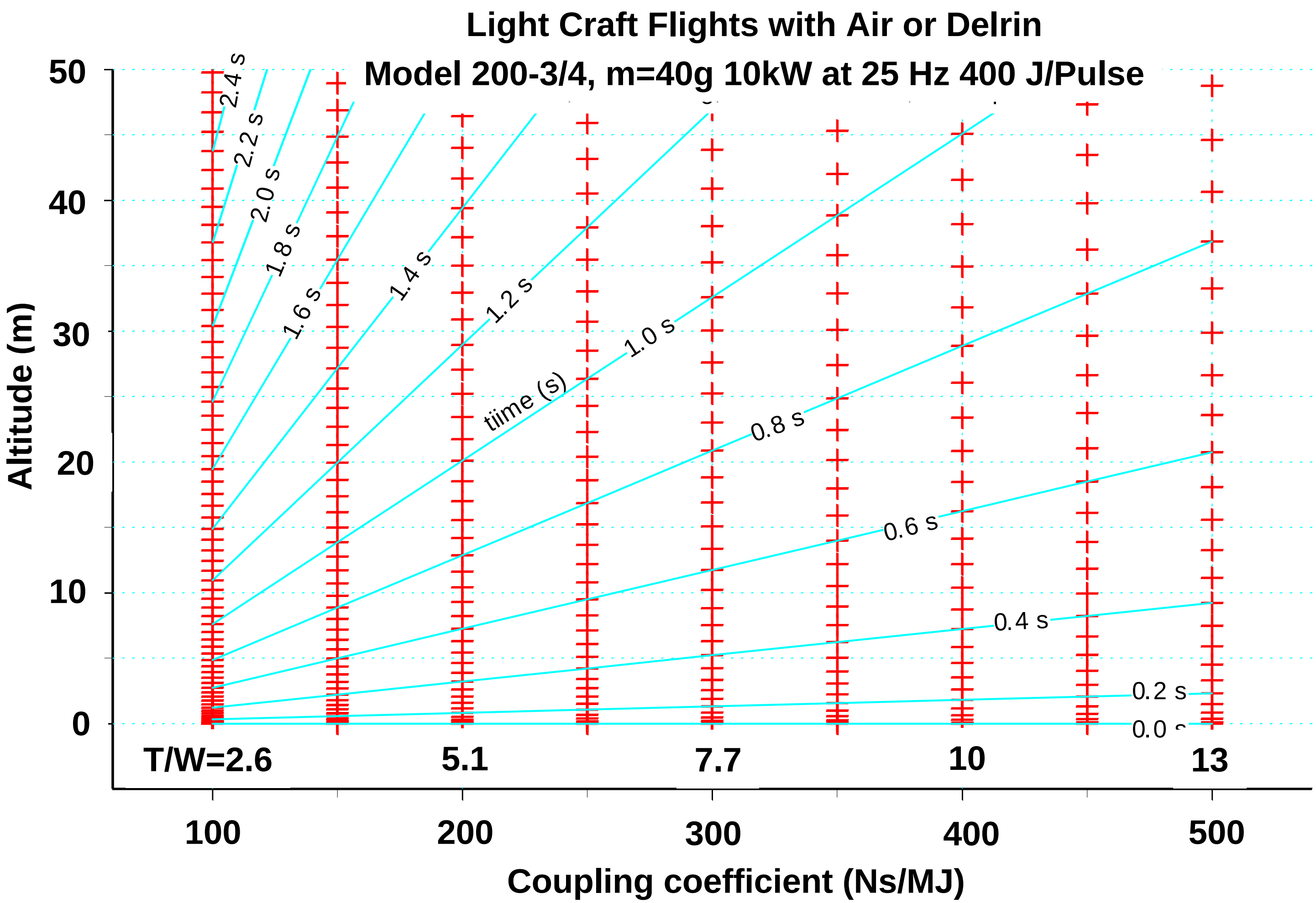
ε(ideal plug nozzle) = 14
m=40g
Delrin surface area ~ 25 cm^2
350 J/25 cm^2/18 μs = 0.8 MW/cm^2
Cm=450 N/MW, E_L/m=5.1 MJ/kg
Ve= 2270 m/s, efficiency = 0.51
T/W=CmP/mg = 11 at P=10 KW

Mini-nozzle
26^o divergence angle



ε= 8
m=7.8 g
Delrin surface area ~ 0.71 cm^2
25 J/0.71 cm^2/18 μs = 2.0 MW/cm^2
Cm=442 N/MW, EL/m=6.3 MJ/kg
Ve=2795, efficiency=0.62

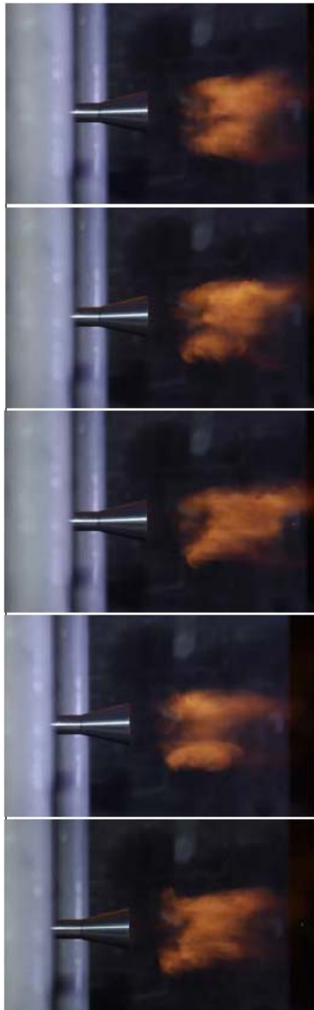
Laser Light Craft Flights



Larson, Mead AIAA 2001-0646

Air Plasma

Mini Thruster 25 J, 18 μs, 0.71 cm^2



11.0 mNs

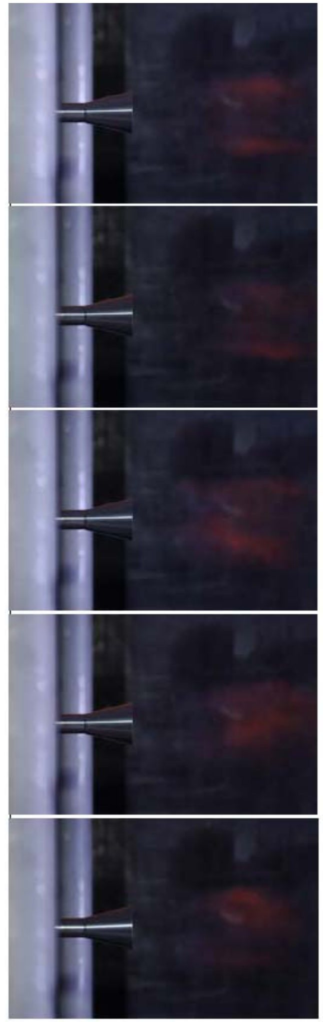
11.3 mNs

10.9 mNs

10.7 mNs

10.2 mNs

Black Ser 9
24.9 J, 18 μs pulse
3.8 mg/shot



10.2 mNs

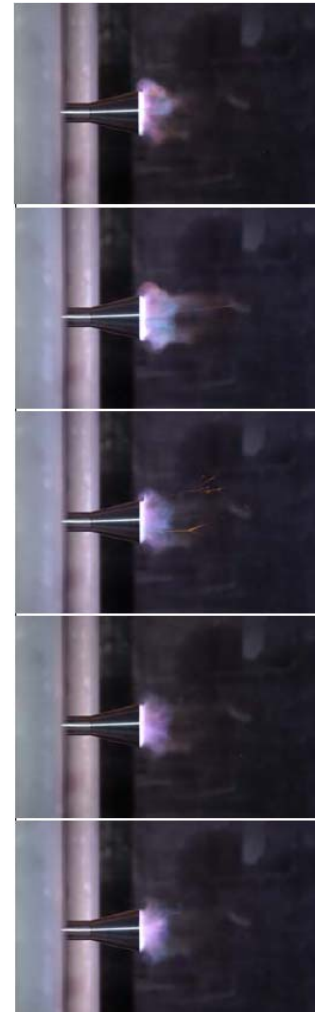
10.9 mNs

12.2 mNs

11.1 mNs

11.0 mNs

White Ser 10
24.9 J, 18 μs pulse
4.0 mg/shot



6.3 mNs

6.9 mNs

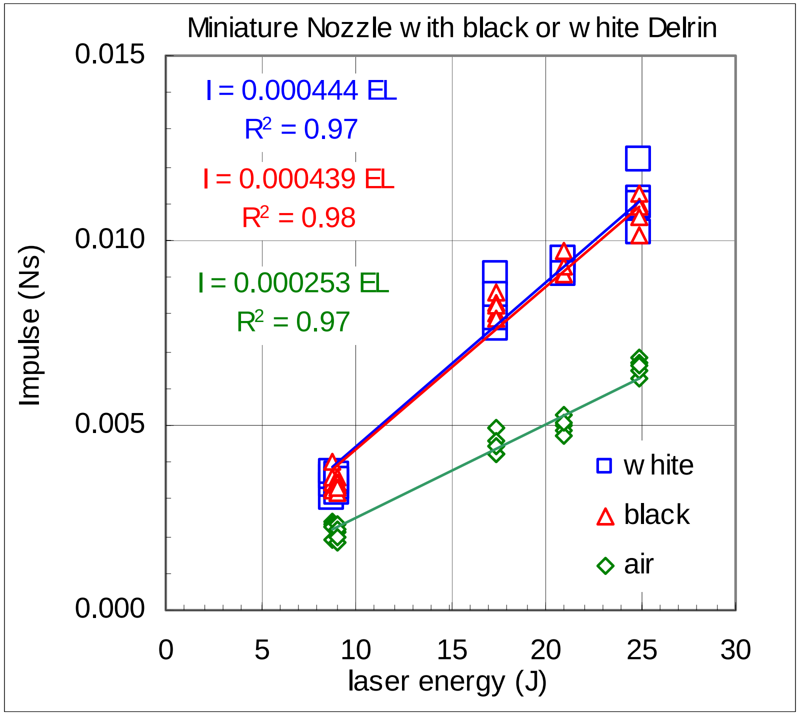
6.5 mNs

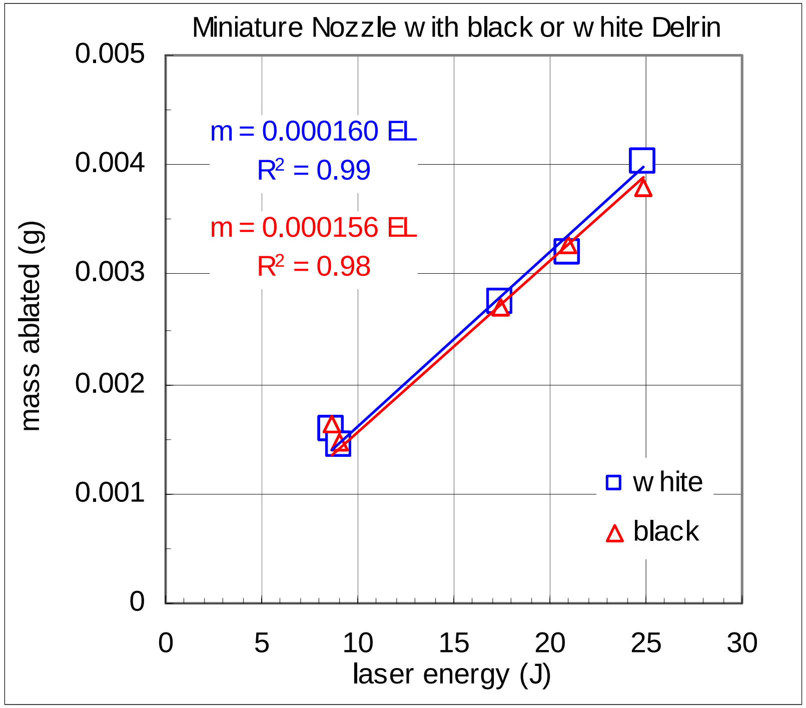
6.7 mNs

6.7 mNs

AIR Ser 11
24.9 J, 18 μs pulse

I, m, E_L for Mini Thruster



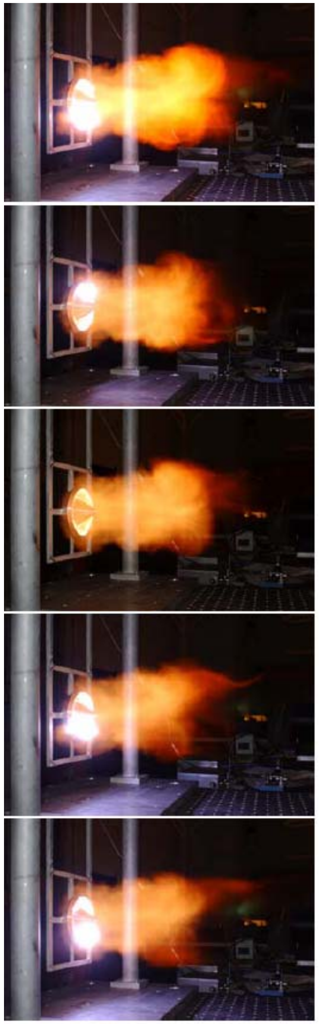


I/E_L = 444 Ns/MJ **m/E_L = 0.160 mg/J**

$$V_e = (I/E_L)/(m/E_L) = 2775 \text{ m/s}$$

$$\text{Efficiency} = \tfrac{1}{2}(I/E_L)^2/(m/E_L) = 0.616 = \alpha\beta\Phi$$

10 cm Light Craft 322 J, 18 μs



139.2 mNs

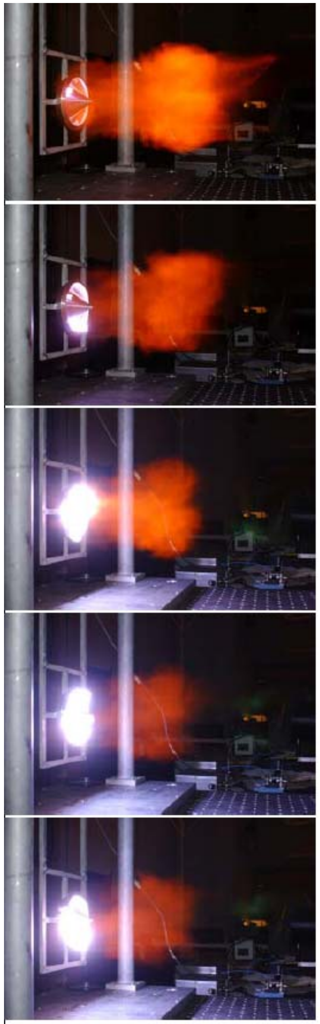
144.8 mNs

153.9 mNs

146.7 mNs

150.2 mNs

Black Ser 7
322 J
59.8 mg/shot



154.1mNs

151.8 mNs

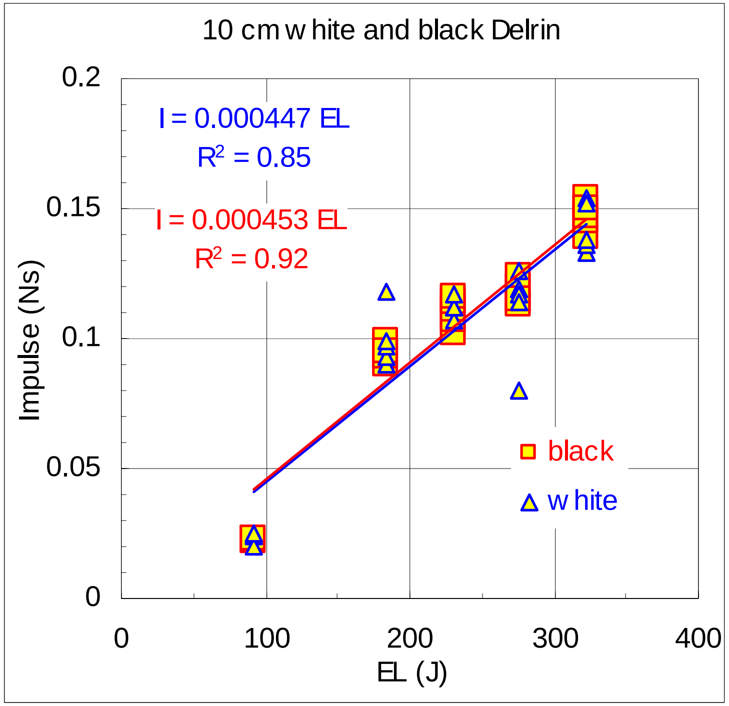
133.0 mNs

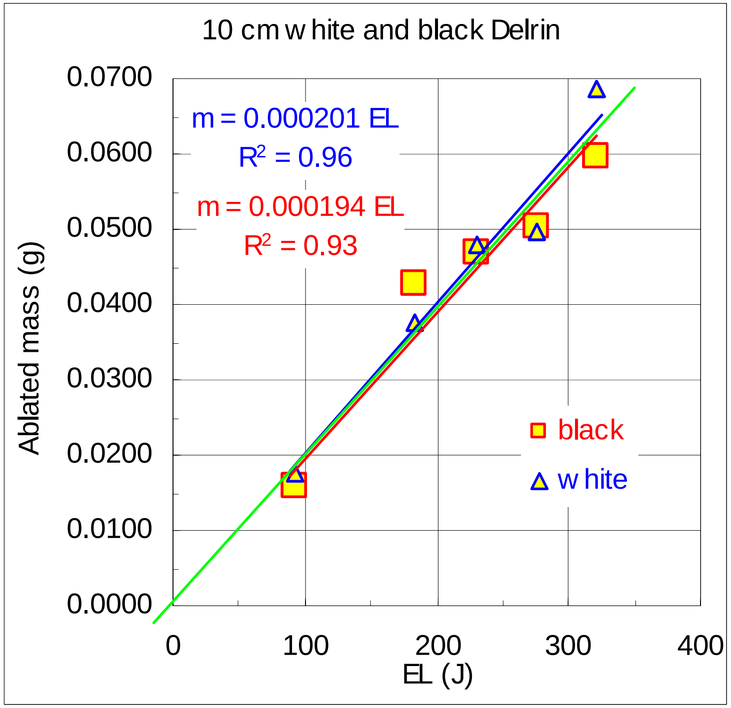
136.1 mNs

137.8 mNs

White Ser 6
322 J
68.7 mg/shot

I, m, E_L for Light Craft 200-3/4





I/E_L = 447 Ns/MJ　　　　**m/E_L = 0.201 mg/J**

$V_e = (I/E_L)/(m/E_L)$ = 2224 m/s

Efficiency = $\frac{1}{2}(I/E_L)^2/(m/E_L) = 0.497 = \alpha\beta\Phi$

CONVERSION OF LASER ENERGY TO JET KINETIC ENERGY

$$Q^* = \frac{\beta E_L}{m_p} \quad \text{Specific internal energy}$$

$$E_{jet} = \frac{1}{2} m_p \langle \mathbf{v_e}^2 \rangle = \alpha m_p Q^* = \alpha\beta E_L$$

$$\mathbf{I} = m_p \langle \mathbf{v_e} \rangle$$

$$\frac{\mathbf{I^2}}{2 m_p E_L} = \alpha\beta \frac{\langle \mathbf{v_e} \rangle^2}{\langle \mathbf{v_e}^2 \rangle} = \alpha\beta\Phi$$

$$\mathbf{C} = \frac{\mathbf{I}}{E_L} = \frac{2\alpha\beta}{\langle \mathbf{v_e} \rangle}\left[\frac{\langle \mathbf{v_e} \rangle^2}{\langle \mathbf{v_e}^2 \rangle}\right] = \frac{2\alpha\beta\Phi}{\langle \mathbf{v_e} \rangle}$$

$$½\mathbf{C} \langle \mathbf{v_e} \rangle = \alpha\beta\Phi \le 1$$

$$\langle \mathbf{v_e}^2 \rangle = \frac{\int_{\rho_i}^{\rho_f} d(\rho \mathbf{v_e}^2)}{\int_{\rho_i}^{\rho_f} d\rho}$$

$$\langle \mathbf{v_e} \rangle = \frac{\int_{\rho_i}^{\rho_f} d(\rho \mathbf{v_e})}{\int_{\rho_i}^{\rho_f} d\rho} = -\frac{\int_0^t \mathbf{F} dt}{\int_{m_i}^{m_f} dm} = \frac{\int_{m_i}^{m_f} d(m \mathbf{v_e})}{\int_{m_i}^{m_f} dm}$$

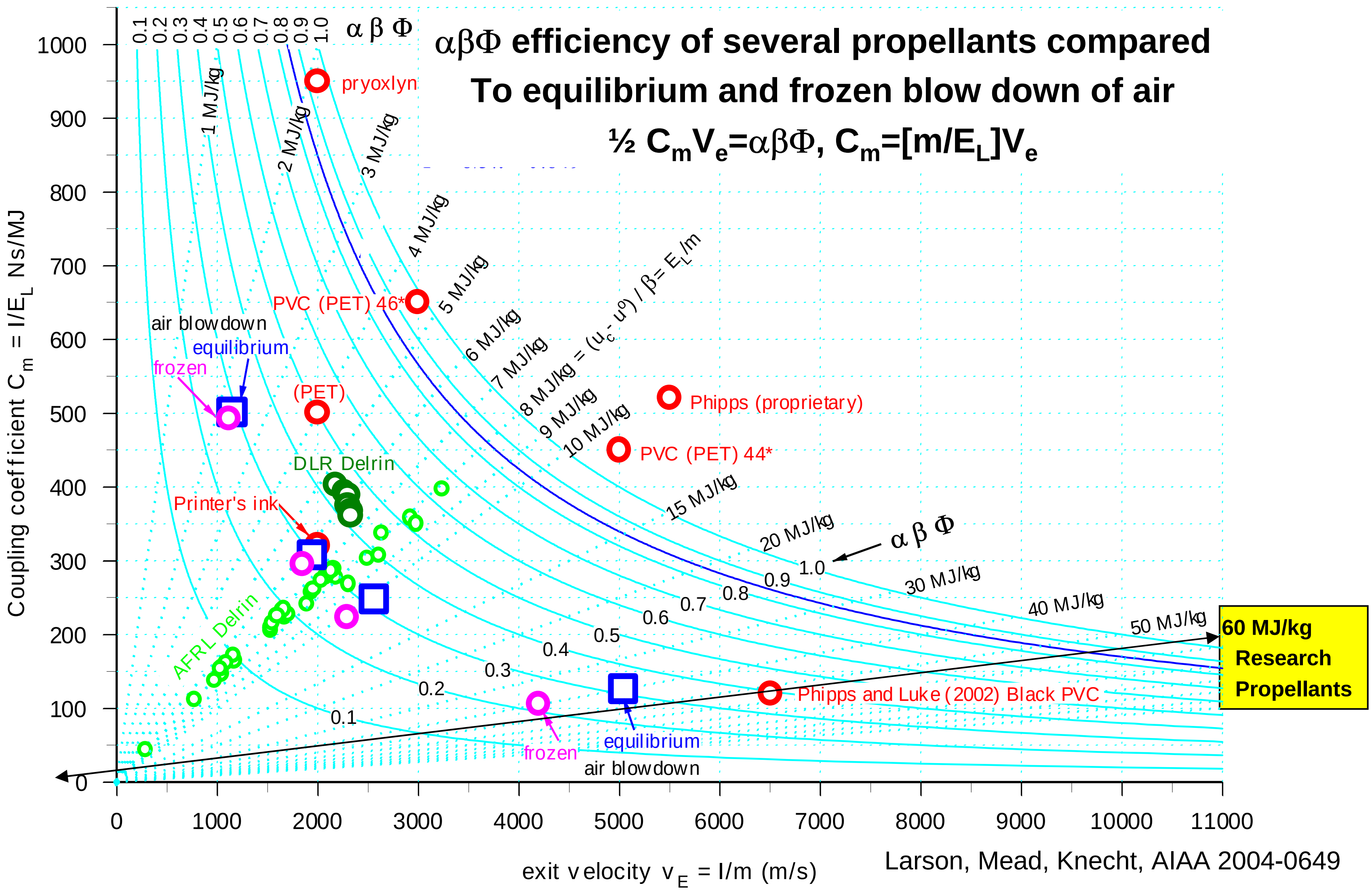
$$\Phi = \frac{\langle \mathbf{v_e} \rangle^2}{\langle \mathbf{v_e}^2 \rangle}$$

For propellants with chemical energy

$$(\alpha\beta\Phi)_{apparent} = \alpha\Phi\left(\beta + \frac{m_p \Delta u_{chem}}{E_L}\right)$$

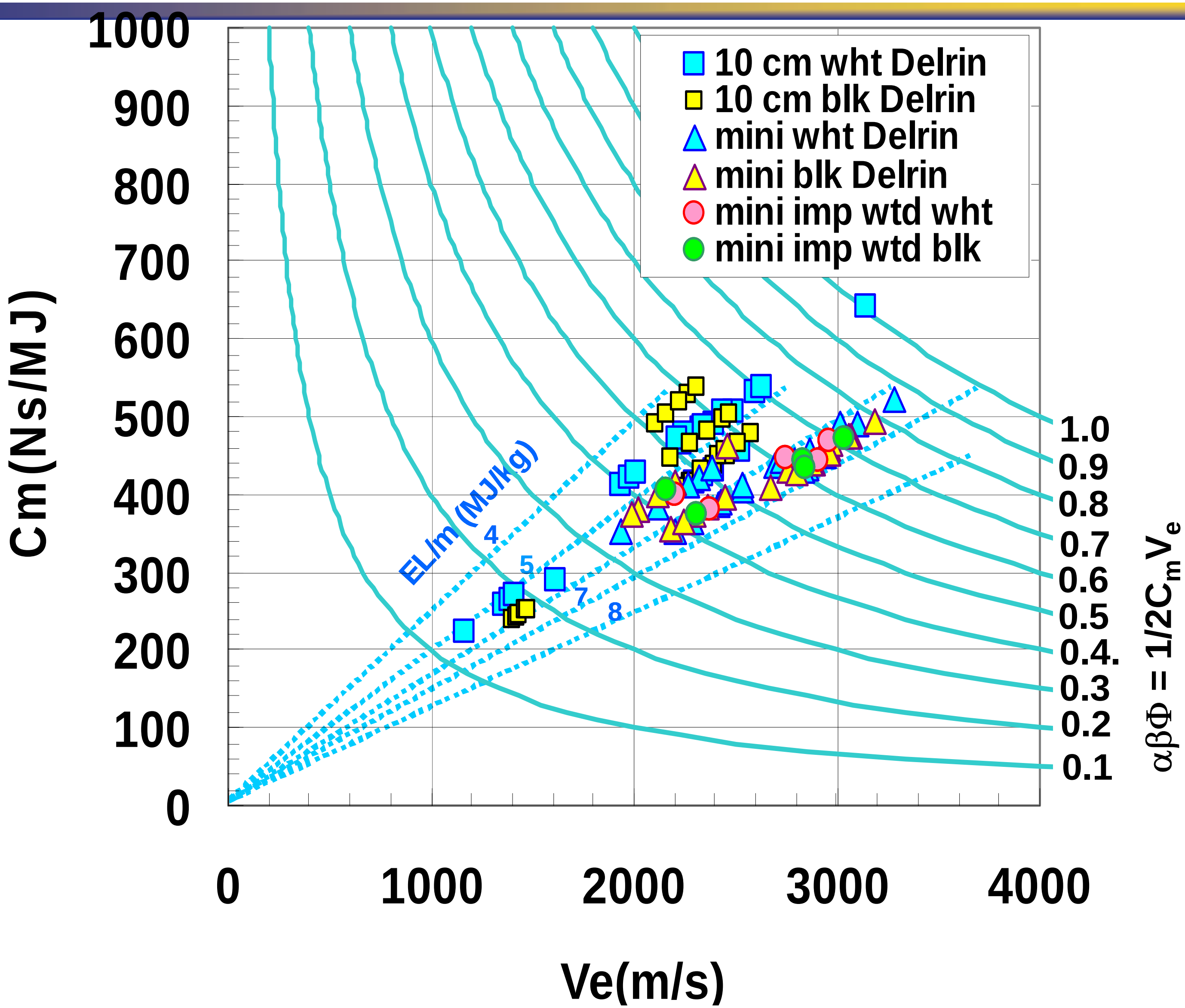
Larson, Mead, Kalliomaa,
AIP Conference Proceedings, ***664*** *(2003)* pp170-181

Performance map of known laser materials and theoretical air



Larson, Mead, Knecht, AIAA 2004-0649

Experimental Results December 2004 200-3/4 Light Craft and Mini Thruster



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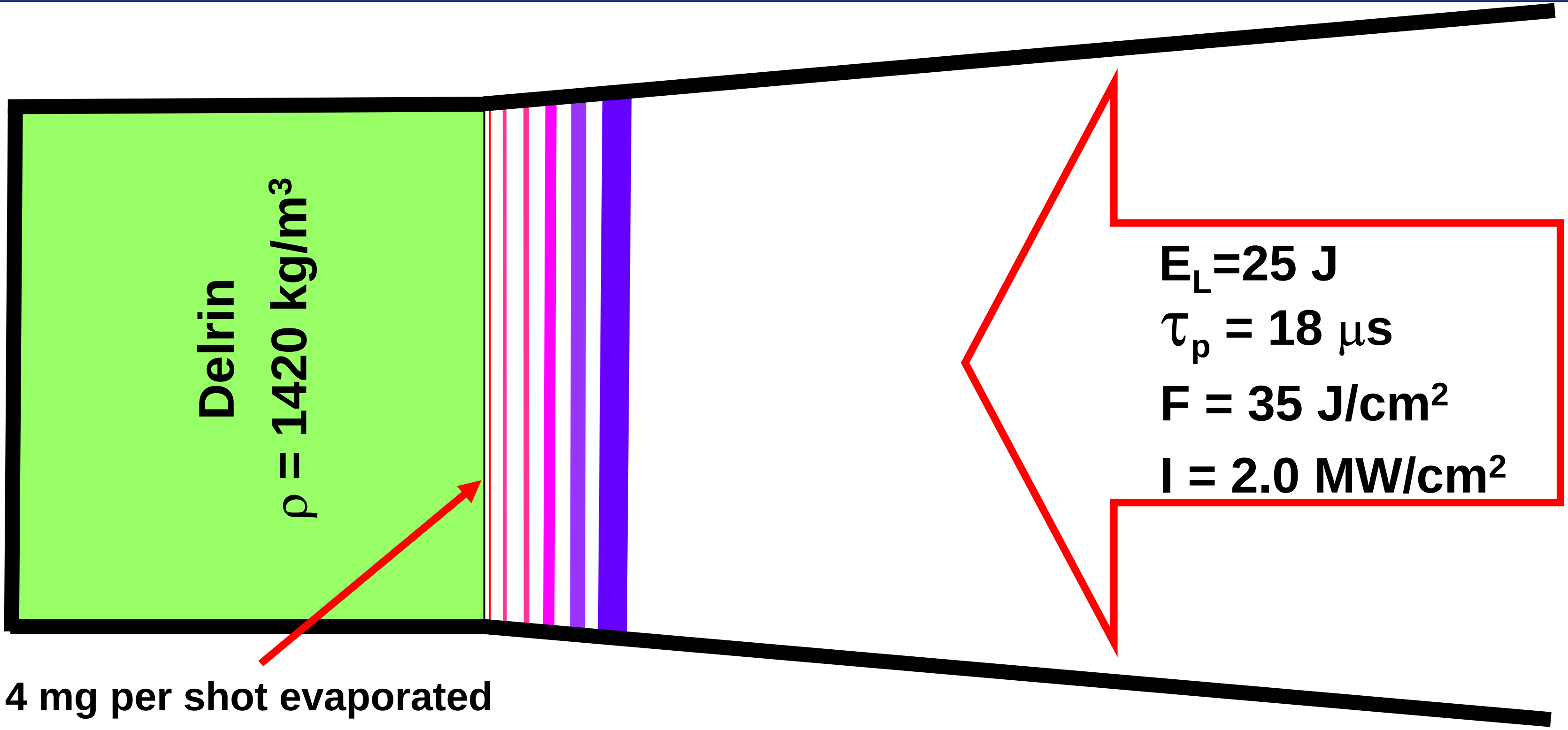
Instantaneous Energy Addition to Delrin



4 mg per shot evaporated

20 μm layer/18 μs

6 J/mg = Q*/β

Specify energy and density of heated layer

Q^*_{delrin} < 6 MJ/kg, ρ < 1420 kg/m^3

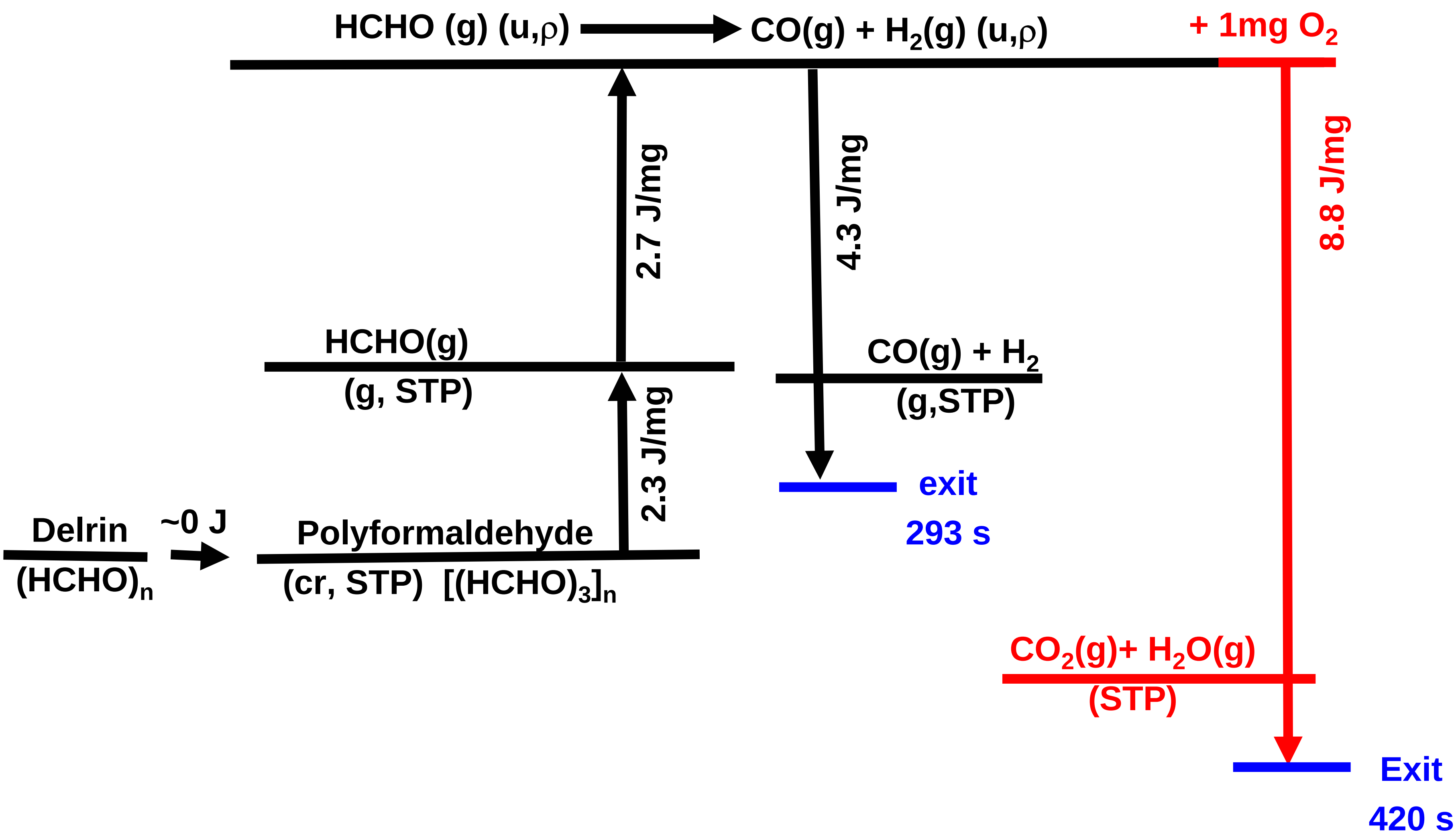
Obtain P ~ 20,000 bar T ~ 3700 K via CEA

Specify expansion ratio

ε = 4, 8, 16, 32, 64

Obtain Isp, thermo props in exit plane via CEA

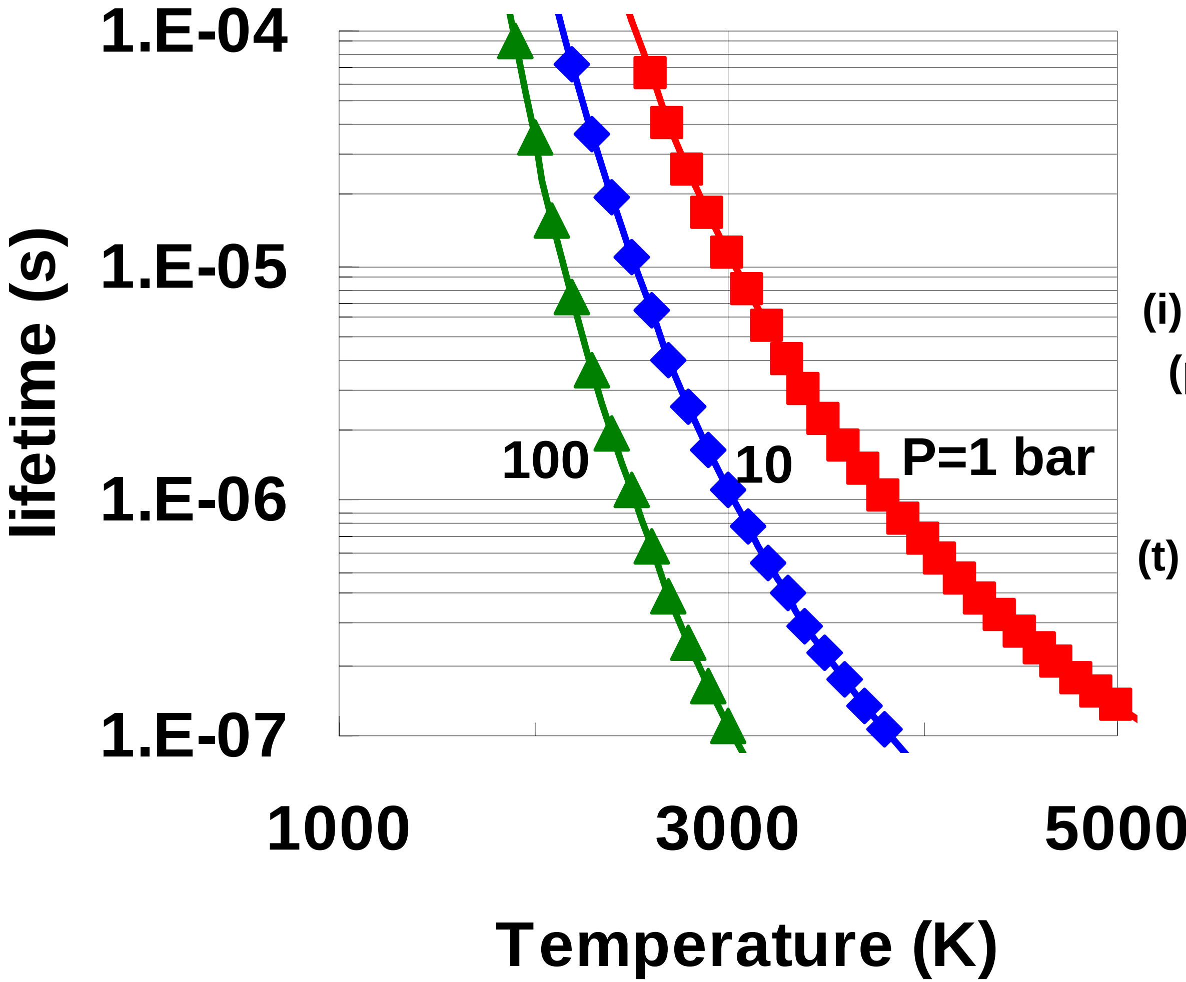
6 J/mg Energy Addition to Delrin



Lifetime of Formaldehyde, $\tau(T,P)$

HCHO + M = H + HCO + M, k=5x10^{15}exp-308kJ/mol/RT cm^3/mol-s

F. Gernot, D. F. Davidson, R. K. Hanson, *Int. J. Chem. Kinet.* 36 (2004) 157



Mechanism:

(i) HCHO + M = H + HCO + M

(p) H + HCHO = H2 + HCO

(t) H + HCO = H2 + CO

(t) H + H + M = H2 + M

(t) HCO + HCO = CO + HCHO

Mole Fractions at Equilibrium

Formaldehyde expansion from P=22694 bar, T=3732K [rho=1227 kg/m^3,u=1.975 MJ/kg]

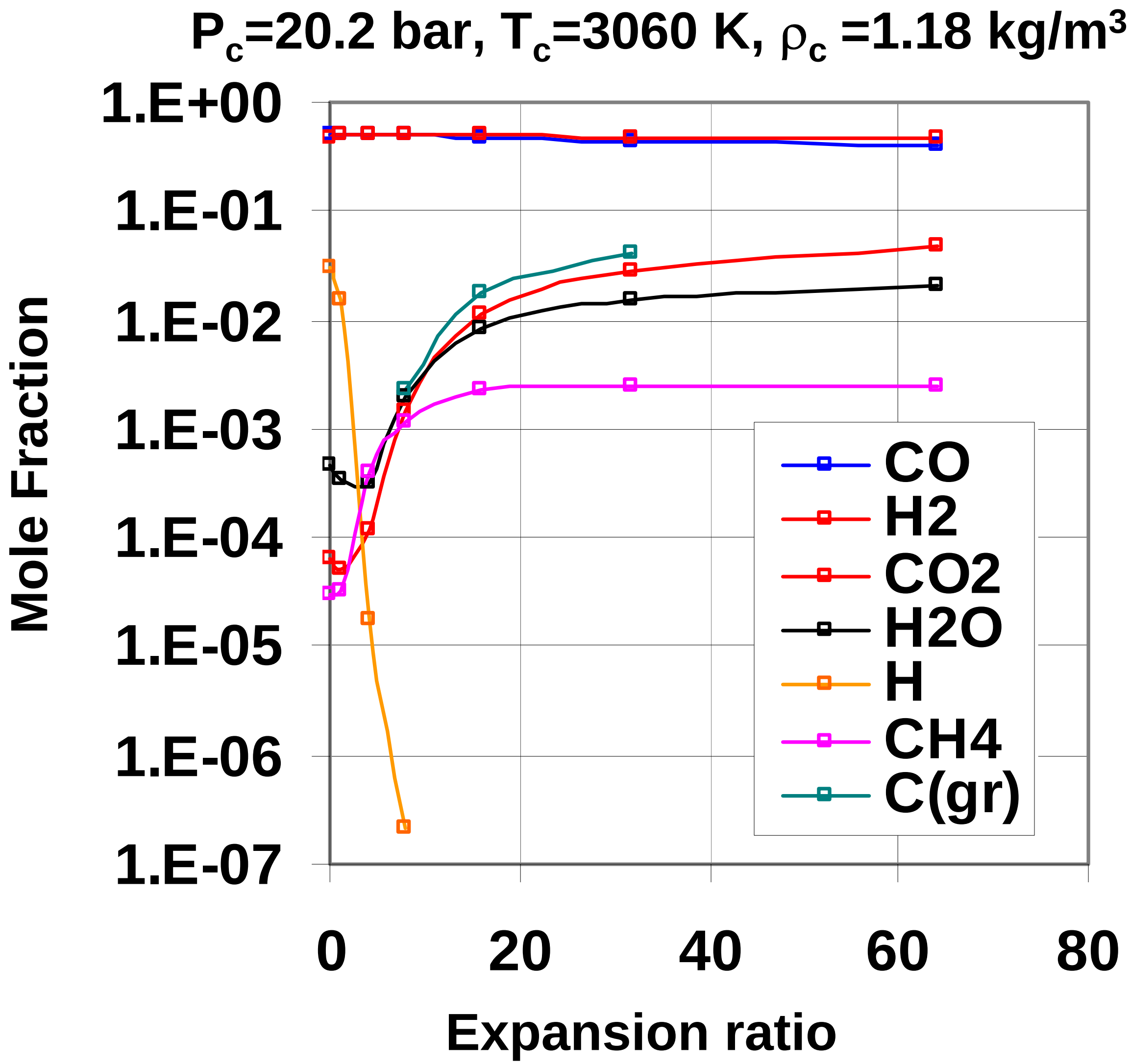
Species	chamber	ε=8	ε=64	species	chamber	ε=8	ε=64
CO	0.47502	0.48415	0.35692	CH3OH	0.00015	0	0
H2	0.39082	0.39891	0.36466	CH3CHO,ethanal	0.00014	0	0
H2O	0.06058	0.04282	0.08215	C3H4,allene	0.00013	0	0
CH4	0.03818	0.05811	0.05318	C3H6,propylene	0.00013	0	0
CO2	0.00856	0.01574	0.05707	CH2	0.00012	0	0
C2H2	0.00742	0.00002	0	C2H2,vinylidene	0.00009	0	0
CH3	0.00472	0.00001	0	CH2OH	0.00007	0	0
H	0.00402	0	0	C3H5,allyl	0.00006	0	0
C2H4	0.00267	0.00014	0	C4H2	0.00006	0	0
HCO	0.00180	0	0	COOH	0.00005	0	0
HCHO	0.00180	0.00003	0	CHCO,ketyl	0.00004	0	0
CH2CO	0.00096	0	0	CH3O	0.00003	0	0
C3H3,2-pryl	0.00039	0	0	C2H	0.00003	0	0
C2H3,vinyl	0.00035	0	0	C3O2	0.00003	0	0
OH	0.00032	0	0	C4H6,butadiene	0.00003	0	0
C2H6	0.00027	0.00005	0.00001	C2O	0.00002	0	0
HCOOH	0.00026	0	0	C2H5OH	0.00001	0	0
C3H4	0.00025	0	0	C3H4,cyclo-	0.00001	0	0
CH3CO	0.00019	0	0	C3H8	0.00001	0	0
C2H5	0.00019	0	0	C4H6,1butyne	0.00001	0	0
				C(gr)	0	0	0.08601

Mole Fractions at Equilibrium

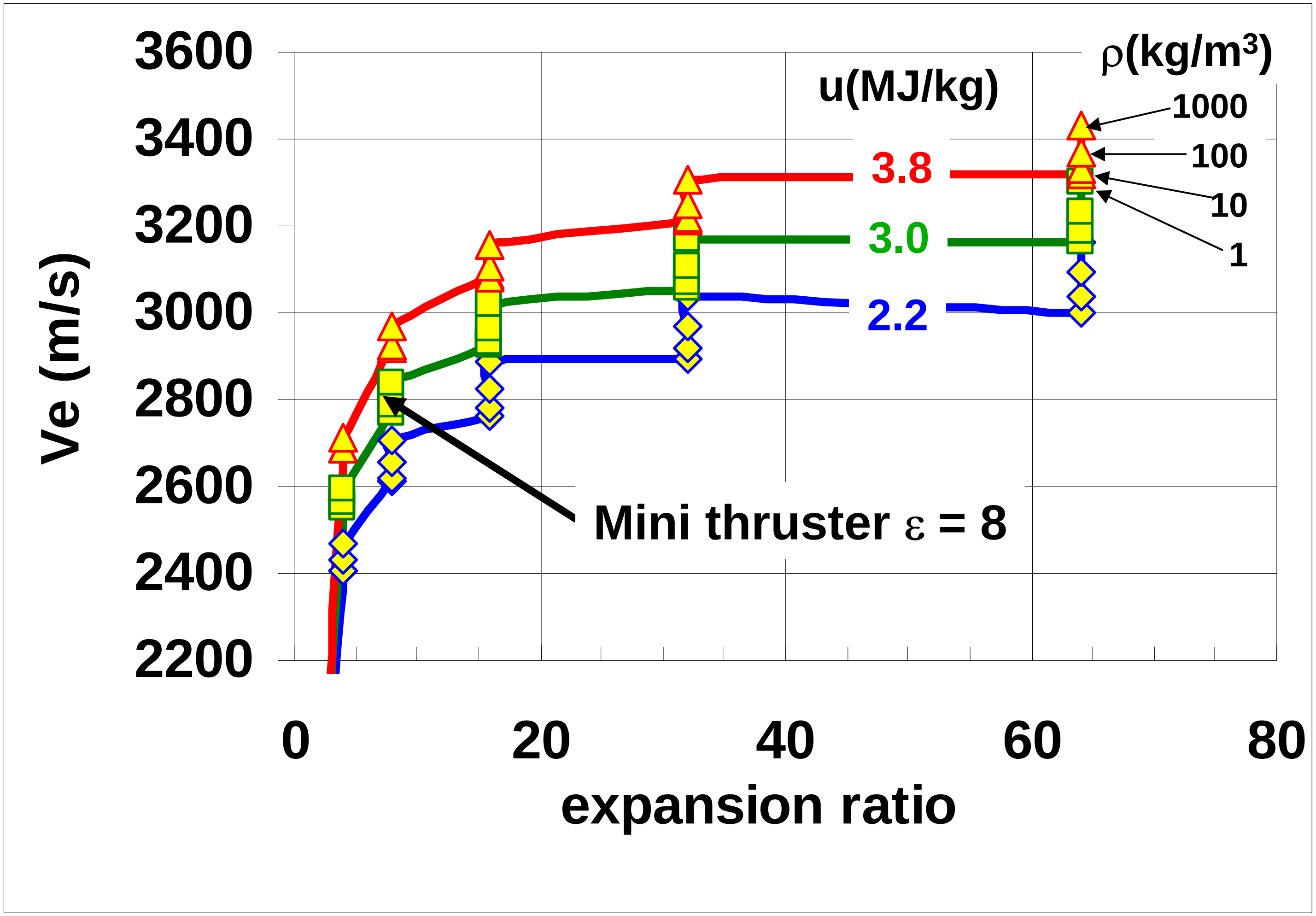
Formaldehyde expansion from P=230 bar, T=3433 K, [rho=12.02 kg/m^3,u=1.907MJ/kg]

mole fractions	Chambr	throat	ε=4	e=8	e=16	e=32	e=64
CO	0.49263	0.49587	0.49955	0.49553	0.47166	0.43233	0.38881
H2	0.47969	0.48865	0.49681	0.4913	0.48006	0.46937	0.46168
H	0.02313	0.01223	0.00003	0	0	0	0
H2O	0.00239	0.00173	0.0014	0.00435	0.01321	0.0231	0.03105
C2H2,acetylene	0.00105	0.00074	0.00002	0	0	0	0
CH4	0.00032	0.00033	0.00176	0.00435	0.00673	0.00753	0.00728
CO2	0.0003	0.00023	0.00041	0.00224	0.01093	0.02605	0.04371
CH3	0.00021	0.00012	0	0	0	0	0
HCO	0.00014	0.00005	0	0	0	0	0
*OH	0.00005	0.00002	0	0	0	0	0
CH2	0.00002	0.00001	0	0	0	0	0
HCHO,formaldehy	0.00002	0.00001	0	0	0	0	0
C2H	0.00001	0	0	0	0	0	0
C2H2,vinylidene	0.00001	0	0	0	0	0	0
C2H4	0.00001	0.00001	0	0	0	0	0
C(gr)	0	0	0	0.00223	0.01741	0.04162	0.06748

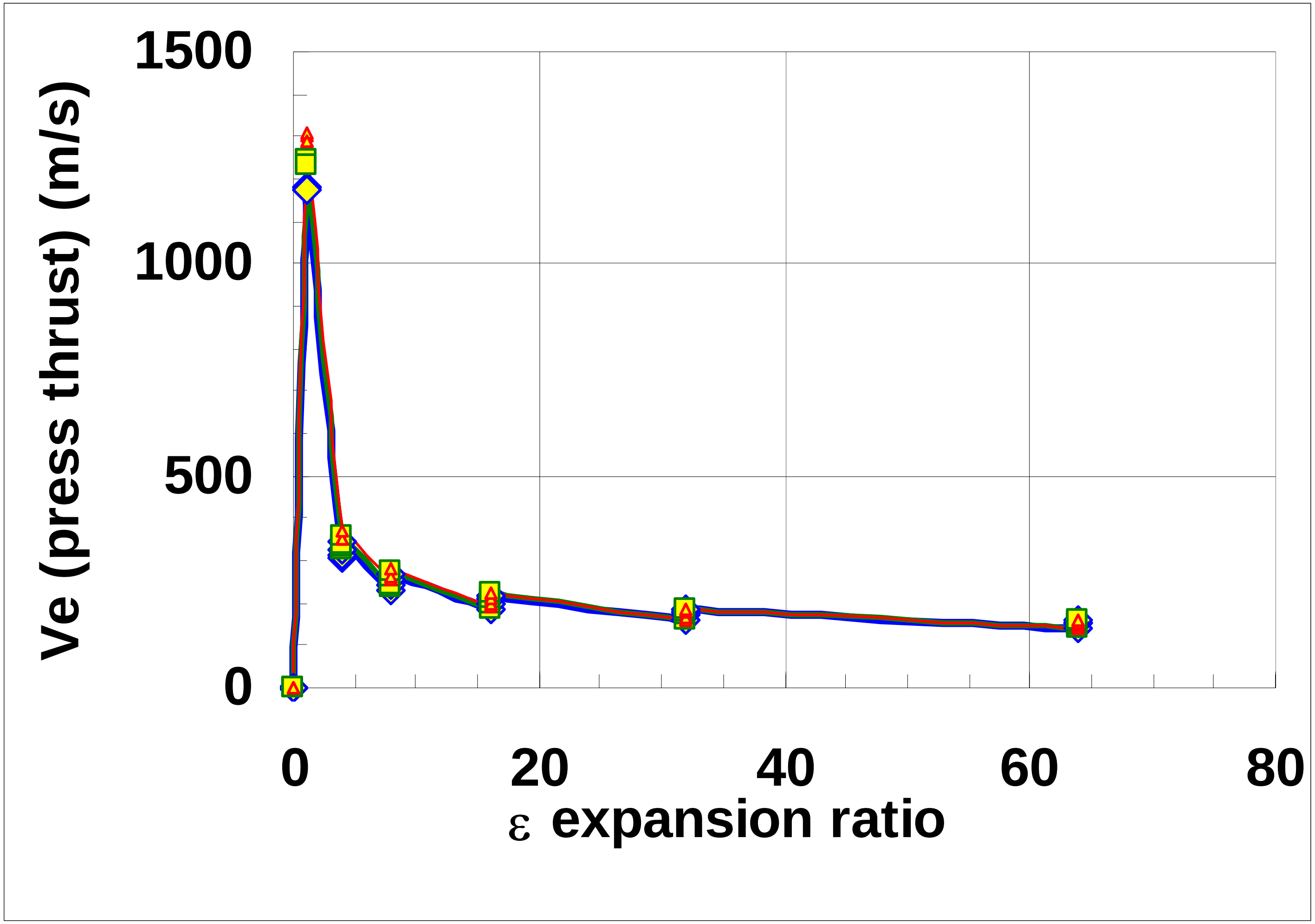
Blowdown from specified initial state (u,ρ) with specified expansion ratio (ε)



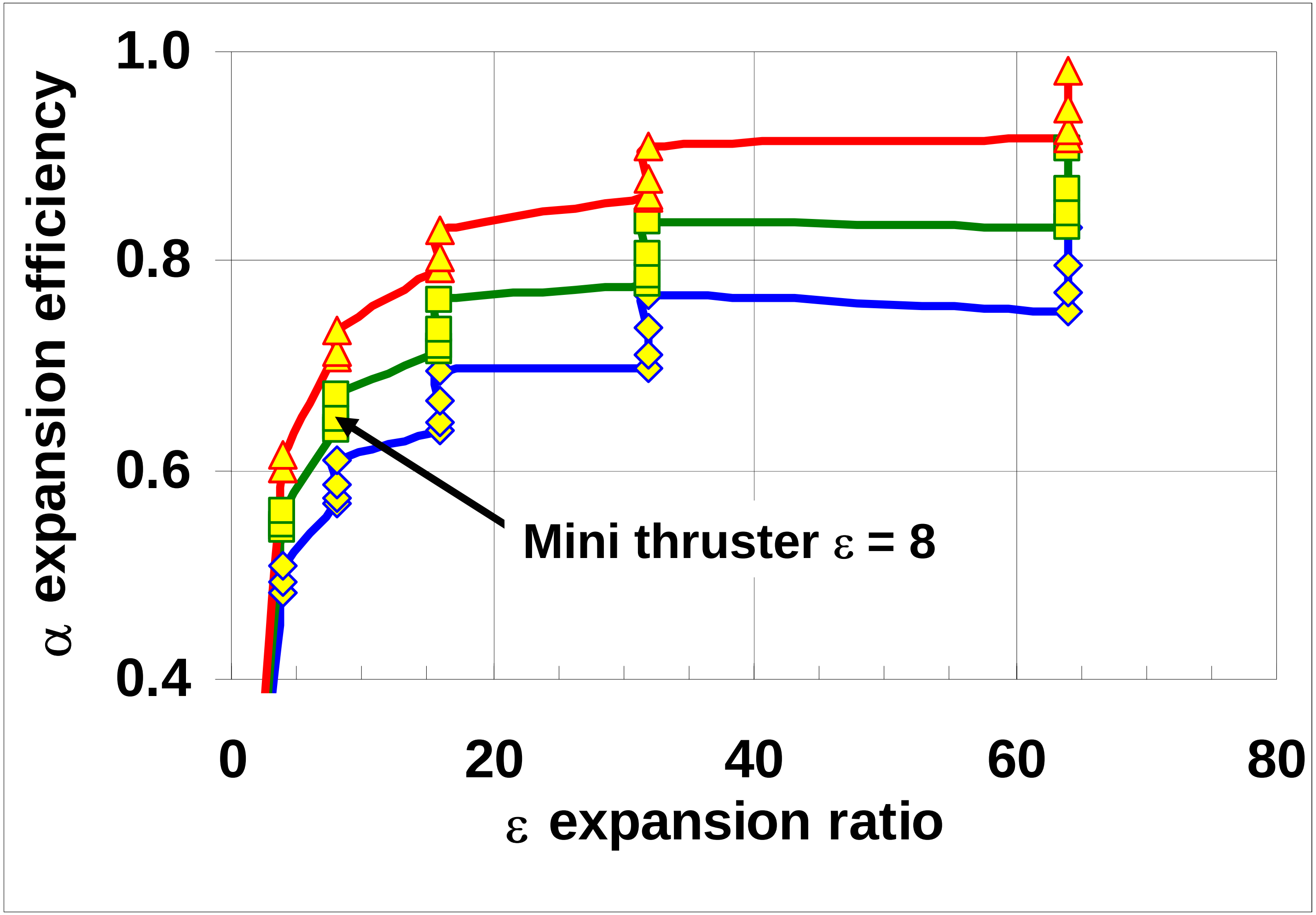
Blowdown from specified initial state (u,ρ) with specified expansion ratio (ε)



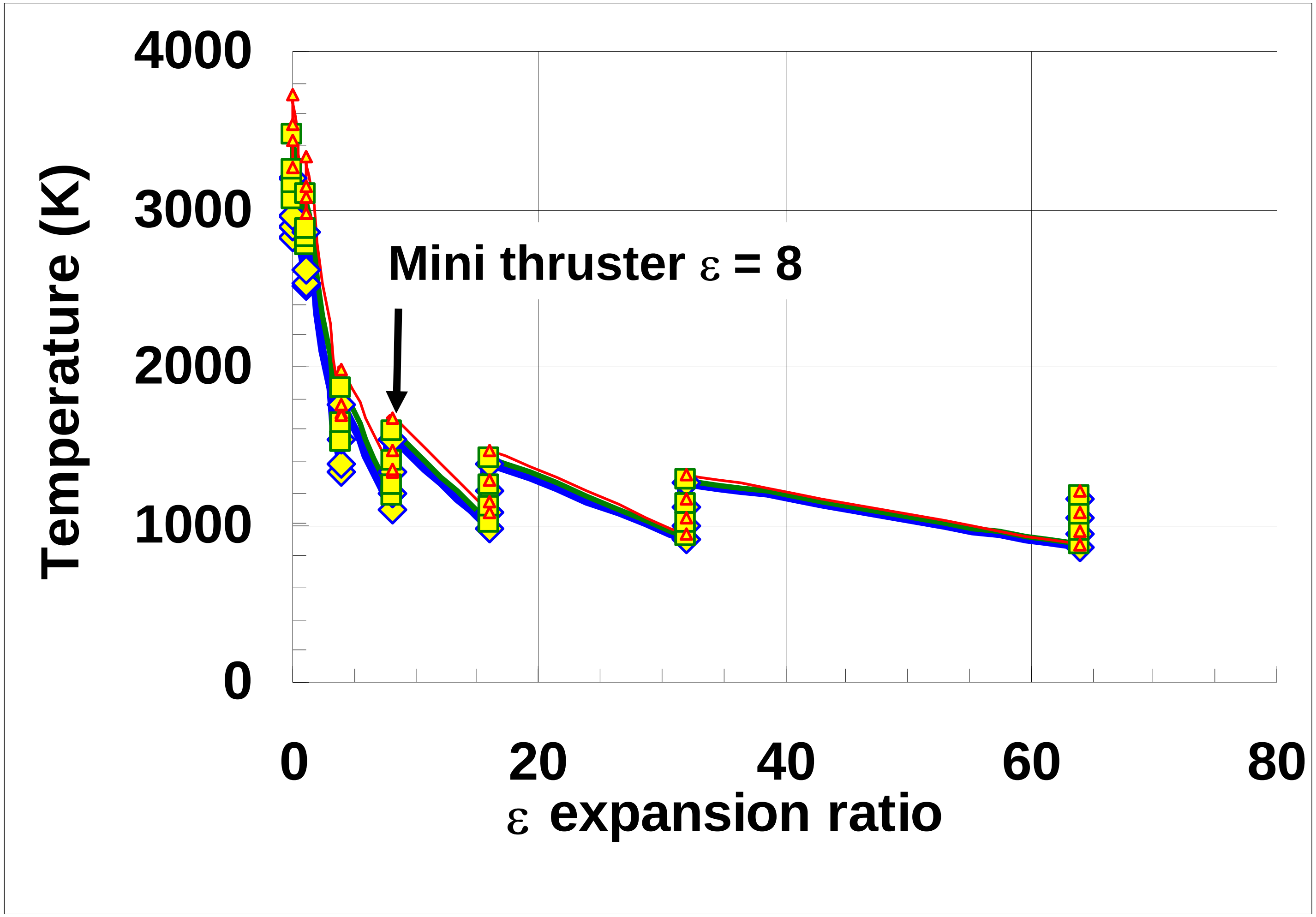
Blowdown from specified initial state (u,ρ) with specified expansion ratio (ε)



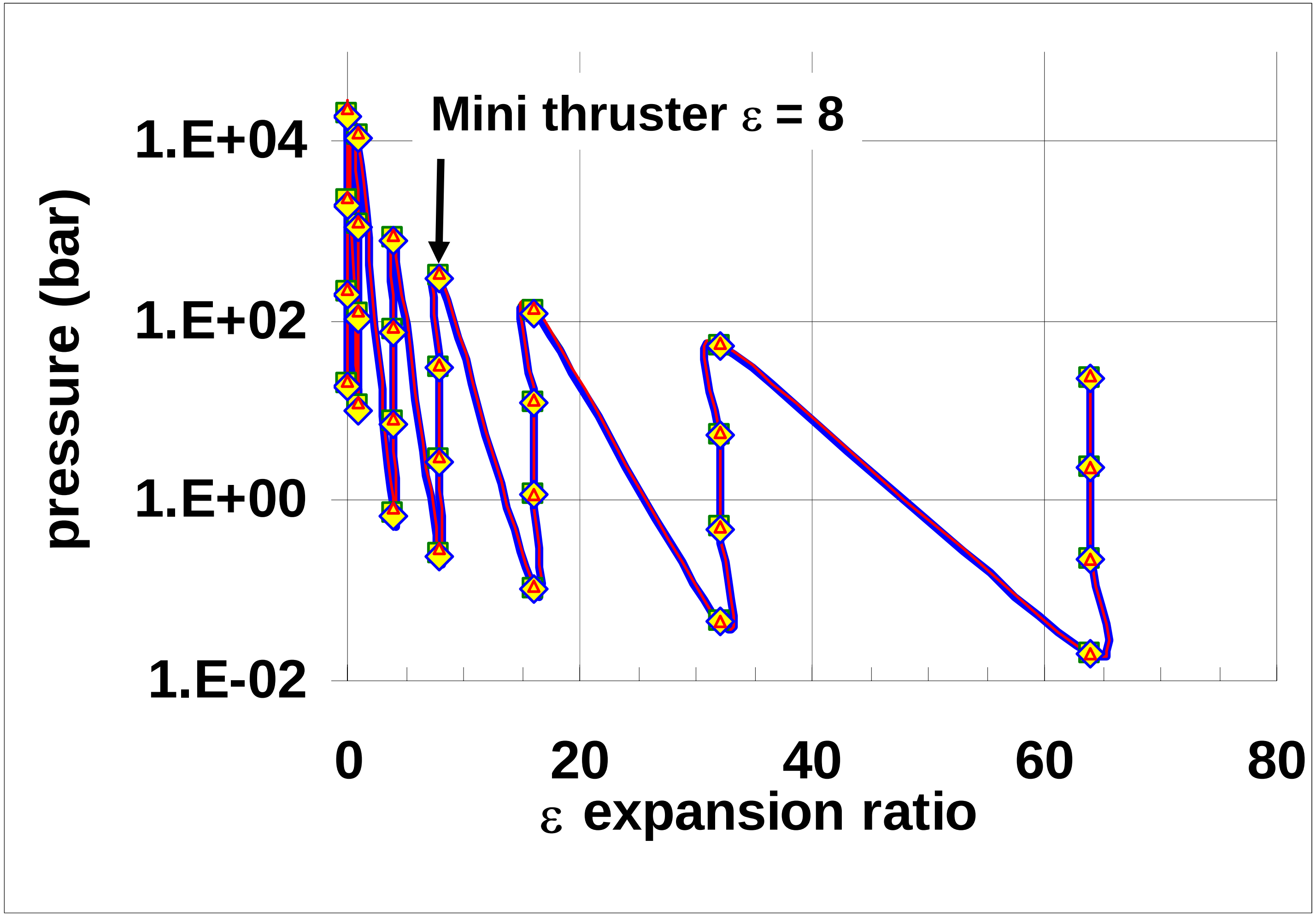
Blowdown from specified initial state (u,ρ) with specified expansion ratio (ε)



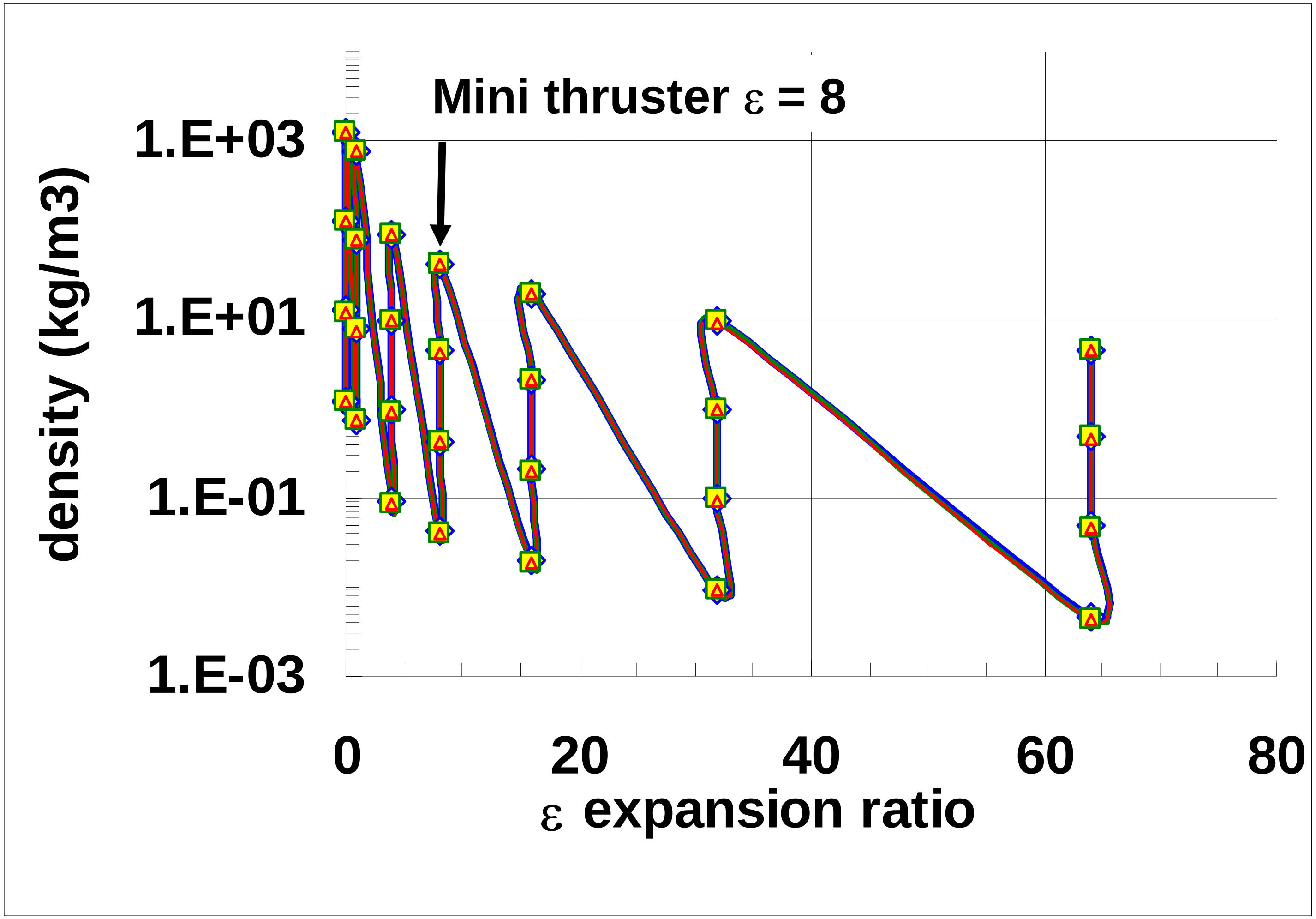
Blowdown from specified initial state (u,ρ) with specified expansion ratio (ε)



Blowdown from specified initial state (u,ρ) with specified expansion ratio (ε)



Blowdown from specified initial state (u,ρ) with specified expansion ratio (ε)



Experimental data (I, EL, m) and derived parameters (Cm, Ve, efficiency, EL/m)

Geometry	**I vs E_L slope**		**m vs E_L slope**		C_m	V_e	Efficiency	E_L/m
	mNs/J	R^2	**mg/J**	R^2	Ns/MJ	m/s		MJ/kg
Mini thruster white	**0.444**	0.97	**0.160**	0.99	444	2775	0.616	6.3
Mini thruster black	**0.439**	0.98	**0.156**	0.98	439	2814	0.618	6.4
Mini thruster AIR	**0.253**	0.97	**-**	-	253	-	-	-
10-cm Model white	**0.447**	0.85	**0.201**	0.96	447	2224	0.497	5.0
10-cm Model black	**0.453**	0.92	**0.194**	0.93	453	2335	0.529	5.2

Conclusions/Work in Progress

- C_m=450 N/MW for Light Craft/Delrin (350 J, 18 μs)
- C_m=442 N/MW for Mini Thruster/Delrin (25 J, 18 μs)
- 51 % efficiency for E_L to jet KE for Light Craft
- 62 % efficiency for E_L to jet KE for Mini Thruster
- Future Experiments
  - Vary pulse width, 5 and 30 μs, expansion ratio, ε = 4, 16, …
  - Increase E_L up to ~ 100 J/pulse in mini thruster
  - Measure time resolved thrust with piezoelectric
  - Develop chemically enhanced ablative propellants
- Future Calculations with Chemical Equilibrium Applications Code
  - Factor pressure thrust into analysis
  - Analyze Chemically Energetic Propellants

THE END

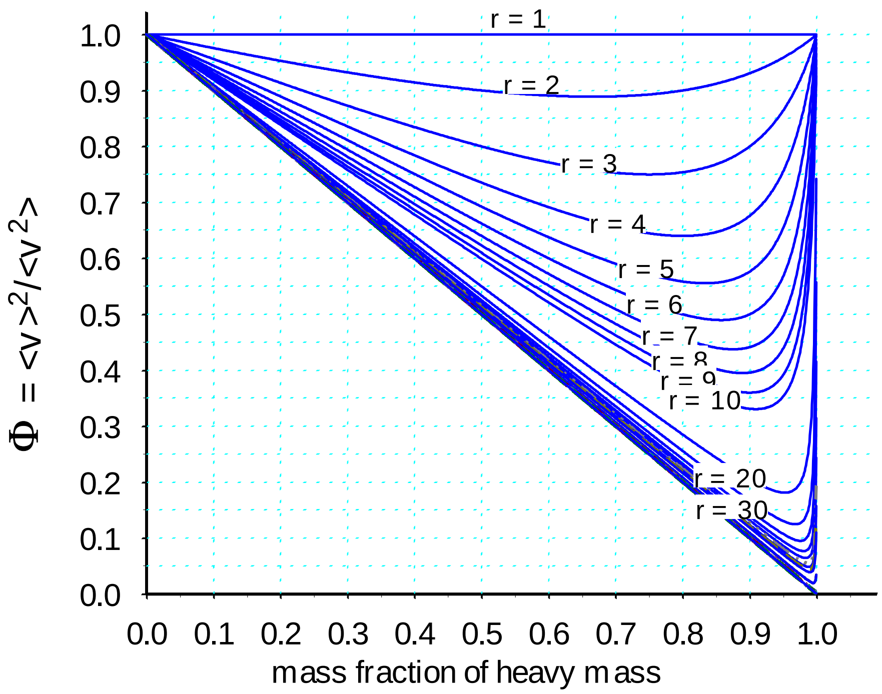
Φ for Bimodal velocity distribution

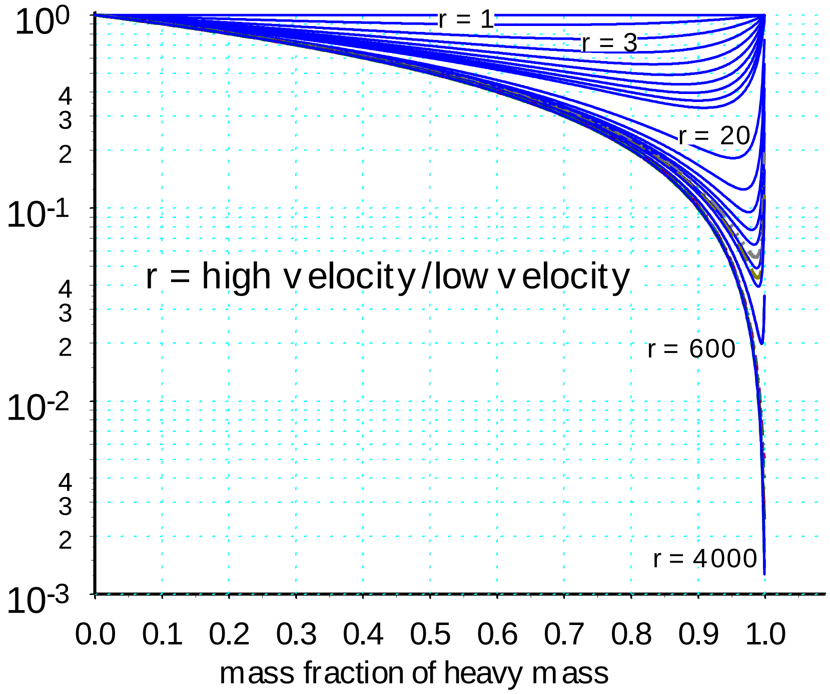
Chunks of propellant — **f_{heavy} mass fraction, v_{slow} velocity**

Hot gases — **f_{light} mass fraction, v_{fast} velocity**

$$\langle v\rangle^2 = (f_{heavy}v_{slow} + f_{light}v_{fast})^2 \qquad \langle v^2\rangle = f_{heavy}v_{slow}^2 + f_{light}v_{fast}^2$$

$$\Phi = \langle v\rangle^2/\langle v^2\rangle = (f_{heavy} + f_{light}r)^2/(f_{heavy} + f_{light}r^2) \text{ where } r = v_{fast}/v_{slow} > 1$$





Divergence Loss